# Space Interferometry Mission: A Systems Perspective

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*Abstract* – In 2006, NASA's Origins Program will launch the Space Interferometry Mission (SIM), a 10 meter baseline optical interferometery instrument, into an earth trailing orbit. This instrument will be comprised of three colinear optical interferometers whose prime mission objective is to perform astrometric measurements of unparalleled accuracy.

NASA has assembled an integrated Jet Propulsion Laboratory (JPL) / Industry team to formulate a reference design to meet the SIM Science objectives. Unique technical challenges have proved to be a formidable task in numerous aspects of the system definition, from component development to system-level integration and test. Parallel activities to develop and test the necessary enabling technologies for SIM are coupled with the ongoing Flight design.

The SIM Project has taken a multi faceted approach to dealing with its numerous technical challenges. Key working groups are addressing specific, integrated areas such as thermal design, dynamics and control, and operations. In addition, detailed integrated models of optical systems, structural dynamics and thermal control systems are being implemented in a large integrated modeling effort in order to validate the system level performance requirements. The implementation of enabling technologies from picometer and nanometer technology testbed programs are crucial to developing a detailed design and mitigating or retiring risk early in the Project development cycle.

This paper describes the current SIM Reference System Design, the key required technologies, the requirements development process and the approach to an integrated systems development.

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## 1. INTRODUCTION

The Space Interferometry Mission (SIM) is a unique mission in NASA's Origins Program. Scheduled for Launch in 2006, SIM will be placed in an Earth-trailing orbit. After an initial 6 months on-orbit calibration and checkout period, the instrument will begin a five year science mission to obtain detailed and highly accurate astrometric measurements of stellar objects and images of stellar debris disks. This mission will make measurements with far greater accuracy than is possible from Ground-based observations.

The SIM design uses three colinear interferometers mounted on a 10-meter long wing (see Figure 1). Each interferometer collects light from two paired siderostats and combines them together to form fringes. Two of the three interferometers will acquire fringes on bright guide stars in order to make highly precise measurements of the spacecraft attitude. The third interferometer will observe the science targets and measure the target positions with respect to an astrometric grid of many thousands of stars evenly distributed around the celestial sphere.

Since the science object will typically be dim (18-20 visual magnitude), the attitude information from the two guide interferometers locked on "brighter" guide stars will be used to point the third (science) interferometer and acquire fringes. Using this "feedforward" technique in the absence of atmospheric disturbances, SIM will achieve its desired accuracy in position measurements for a single observational period. Three primary observational periods have been defined to support narrow angle, wide angle and reference grid closure astrometric objectives. The Narrow Angle measurements require certain levels of system stabilities over 5 minute periods. The Wide angle astrometric observations are less stringent, requiring system level stabilities for periods of up to one hour. The Grid work requires system stabilities and continuous measurements for periods of up to two weeks at certain times throughout the mission.

Three major organizations are combining to develop the SIM Flight System. JPL leads the overall System development and Real-time Control Subsystem while TRW has the responsibility of developing the avionics, structures (including the Precision Support Structure or PSS) and mechanisms. They are also responsible for the final integration and test called Assembly, Test and Launch operations (ATLO).

[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

Lockheed Martin is responsible for the development of the instrument Starlight and Metrology Subsystems as well as instrument integration and test.

## 2. FLIGHT SYSTEM DESIGN DESCRIPTION

*Overview*

The Flight System consists of three simultaneously operated optical Michelson stellar interferometers and an external metrology truss that monitors the relative orientations of the three baselines. The system consists of optics, actuators, sensors, and computers for acquisition and tracking of the stellar fringe pattern, the desired science data. The maximum science interferometer baseline is 10 meters. At any time, one interferometer is dedicated to taking science data while the other two act as "guide" interferometers to determine the orientation of the baseline of the science interferometer. Using "bright" stars, these guide interferometers act as a high precision star tracker for the science interferometer.

The fundamental design of a single interferometer requires that the pointing subsystem acquire the starlight photons using siderostat mirrors in each arm of the interferometer. The starlight is sent through a series of relay optics in the PSS, via course and fine stage delay lines for optical path compensation, to beam combiners. The beam combiners combine the light to form fringes on a CCD detector.

A switchyard transfers light from any given siderostat bay into any selected delay line, allowing measurements to be made at a number of different baselines. Use of multiple baselines enables a technique called synthesis aperture imaging and also provides for astrometric baseline redundancy. It is critical that the three interferometer baselines are co-parallel. This is due to the fact that the two guide interferometers provide attitude information in two of the three angular directions. The third dimension is the roll about the baseline vector. Sensing of this direction is significantly relaxed if the interferometer baselines are parallel to one another.

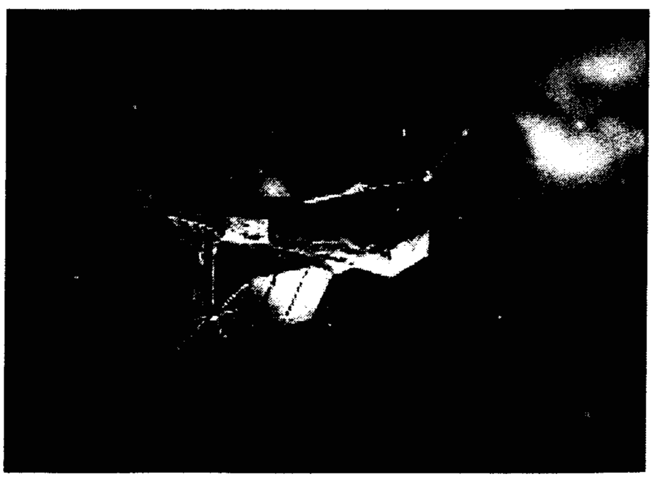

Figure 1 SIM Artist Concept

The metrology subsystem measures distances in the interferometer critical to the high precision angular measurements. The metrology subsystem utilizes heterodyne metrology laser gauges to measure the interferometer baseline length and the internal optical path lengths. The science requirements translate directly to a requirement on the accuracy of the metrology gauges. The metrology gauges will have to measure relative changes in internal pathlength with an accuracy of approximately 20 picometers.

The metrology subsystem is subdivided into the metrology fiducials, the beam launchers and the metrology sources. The fiducials serve as the endpoints of the measurement system. The beam launchers inject laser light to measure the distance between the fiducials. Finally, the metrology source generates the optical signal and frequency offsets necessary to derive the metrology phase differences.

*Pointing System*

In SIM, the pointing subsystem consists of seven siderostat bays distributed along the PSS creating up to four separate, co-linear baselines. Each siderostat bay holds a siderostat and a 40-centimeter flat mirror pointed 30 degrees from the optical axis of the beam compressor. The siderostat uses two-axis flexures and voice coils to move the mirror over a 7.5-degree range [1]. The pointing system has both coarse and fine actuators. The coarse actuator acquires stars over a 15-degree field of regard without reorienting the spacecraft. The fine actuator provides high-precision pointing control required for high-visibility stellar fringes. A coarse pointing sensor, known as the Siderostat camera, is also located in the front-end pointing system. This camera provides feedback used to align the starlight on the optical detectors.

The siderostat actuator has high-precision rotary encoders to provide a pointing resolution of 20 milliarcseconds. The system is also designed so that the siderostat can, in Calibration Mode, articulate to a position that it is facing normal to the beam compressor, thus reflecting an optical calibration signal back into the optical train. The beam compresses the stellar beam from a 33-centimeter, collection-aperture diameter to a 4.5-centimeter-diameter beam. This compression enables the use of smaller optics in the remainder of the optical train, for calibration between the starlight wavefront path and the path as sampled by the internal metrology system. A corner cube at the center of each siderostat mirror defines the end point of the interferometer baseline. The corner cube is physically contacted to the siderostat surface such that the vertex is coaligned with the mirror surface and the two siderostat axes. Translation actuators underneath each siderostat mirror are used to align the baselines after the initial instrument deployment to within 10 micrometers of being co-linear. The external metrology will monitor the misalignment between the baselines.

Starlight exiting the beam compressor is sent to a Fast Steering Mirror (FSM), providing the high frequency pointing control of the starlight. The FSM is used to adjust the incoming starlight beam wavefronts in order to reduce the tilt in the system. From there, starlight proceeds to a turning mirror, which injects the starlight into the remainder of the optical train.

In addition to the starlight collection and pointing optics, metrology beam launchers are also mounted in the Siderostat bay and aimed at the Metrology "kite" vertices approximately 9 meters away. Each siderostat bay houses four beam launcher assemblies that measure the distances between the metrology boom vertices and the siderostat fiducials.

*Delay Lines*

From the front-end pointing system and relay optics, the starlight goes through an optical switchyard and transfers to the optical delay lines, which modulates the pathlength difference between the two arms of any given interferometer. Like the pointing subsystem, the delay lines have multiple stage actuators. The coarse stage, consisting of a band drive and stepper motor, moves the entire cat's-eye assembly by up to 2 meters as necessary to acquire fringes for stars within a 15-degree field of regard. The fine actuator stages, using both voice coils and Piezo-electric Transducer (PZT)s, provide high-bandwidth pathlength modulation to control the optical path difference precisely and reject jitter from onboard disturbance sources, such as reaction wheels or delay lines. A voice-coil stage moves the cat's-eye assembly over a 1-centimeter range at low frequencies (<10 hertz), and a PZT stage provides the high-bandwidth actuation (10-1,000 hertz) with a stroke of a few micrometers. During normal observations, the delay-line coarse stage will be locked down and only the voice-coil and PZT stages will be used for pathlength control. Both those stages will be momentum compensated to minimize disturbances induced by the delay line to the rest of the instrument.

*Astrometric Beam Combiner*

The final element in the light path is the astrometric beam combiner which includes the white-light fringe camera detectors and internal metrology beam launchers. At this point, the delay lines have compensated the pathlength difference for light from the two arms of the interferometer. A white-light fringe can form as soon as light from the two arms is combined. The camera or Fringe Tracker, in the beam combiner system, records this fringe pattern. The fringe position is then used as both the science data and as a sensor signal for the delay-line actuator allowing maximization of the signal. The beam combiner also contains a detector, called the Angle Tracker, to measure the tilt of the incoming wavefronts. This sensor controls the fast-steering mirror in the pointing subsystem.

The stellar fringe is spectrally dispersed using a prism to provide phase and visibility information at different wavelengths. These data are then used to extract pathlength information by the control system.

In addition to collecting the science data, the beam combiner generates the control signals for the delay lines and the pointing subsystem. For this purpose, the starlight pupil plane is divided into three regions. The inside region is used to propagate the internal metrology beam from the combiner to the optical fiducials on the siderostat mirrors. Light from the middle annulus is combined to form the stellar fringe (the science data measurement) and is sensed by the Fringe Tracking camera. Light from an outside annulus is used to determine the wavefront tilt, and is sensed by a second camera, the Angle Tracking camera.

*Metrology*

The metrology subsystem consists of three primary gauging measurements: Absolute Metrology, External or Baseline Measurement and the internal or pathlength measurement. Optical fiducials, located in front of the siderostat, define the interferometer baseline. The external metrology system measures the length of the interferometer baseline (and relative baseline orientation). The internal metrology measures the optical path from the beam combiner to the optical fiducial. Heterodyne metrology gauges are used to monitor the distances between the optical fiducials. A separate internal metrology gauge is used for each arm of the interferometer, and is injected into the center of the starlight beam inside the beam combiner. This metrology beam will measure the path from a fiducial inside the combiner to the baseline fiducials. The internal metrology samples the center of the same optics that transmits the starlight and is referred to as sub-aperture metrology (SAM).

The external metrology truss measures the lengths and relative orientations of the three interferometer baselines. A 9 meter metrology boom is deployed after launch. A 4 x 4 meter

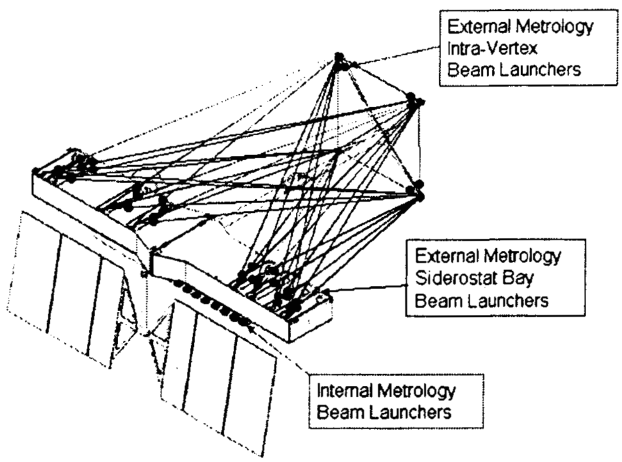


Figure 2 Metrology System

external metrology truss or "kite" is deployed containing articulating reference fiducials that are used to triangulate on the position of each of the siderostat fiducials ( see Figure 2). Only three vertices of the "kite" are required to perform the triangulation; the fourth vertex is for redundancy. These vertices are actuated to maintain a 10 micron stability requirement of the starting position of the vertex position relative to the baseline, for the entire 5 year mission. An external metrology beam-launcher assembly is located at three of the four vertices of the metrology "kite". In addition to the 28 siderostat bay metrology beams measuring the distance between the siderostats and the "kite" vertices, six additional beams are used to measure the distances between the fiducials in the "kite". Each "kite" beam-launcher assembly consists of two beam launchers and a multiple corner cube fiducial in a temperature stable enclosure.

The metrology subsystem uses double faced corner cubes as the optical fiducials for both the external and internal metrology gauges. One face of the corner cube is used by the external metrology gauge to measure the baseline length. The other face of the same corner cube is used as a common endpoint for all four internal metrology gauges. It is critical that the vertices between the different corner cubes are co-aligned in order to minimize the offset between the external metrology measurement and the internal metrology measurement. [2]

*Real-Time Control*

The Real-Time Control subsystem includes the electronics, software and control algorithms necessary to support and run the interferometer. The SIM instrument will need to operate with limited intervention from the ground, and therefore must perform important functions with a high level of autonomy and reliability. These functions include initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, slew, and diagnostics. The Real-time software will play the central role in performing these functions. The software will have to operate the instrument on a distributed set of computers.

The instrument flight software implements the set of in-flight real time command, data, and control functions required to operate the SIM flight instrument. Instrument command and data functions include startup; instrument sequence decoding and execution; storage of science and engineering data and packetization packaging for telemetry down-link. In addition to normal instrument operations, the flight software will provide the functionality for ground testability and some level of fault protection enabling autonomous operation without ground assisted reconfiguration. Additionally, the instrument flight software will need to communicate with the Spacecraft Flight software for the routing of both uplink and downlink data. The interface is especially important as it is the Spacecraft that handles all Ground System to Flight system communications. The instrument data is sent to the spacecraft system to be stored on a solid state recorder.

The SIM instrument software architecture is derived from existing ground interferometer designs as well as having some level of commonality with the Space Technology–3 (ST-3) interferometry mission. The software allows the use of multiple computers to control the interferometer and enables flexibility in the design of the flight instrument electronics and hardware.

The control functions enable the instrument to track on a stellar fringe and monitor the critical instrument parameters through the metrology system. The control system includes alignment, pointing control and pathlength control. Alignment control establishes and maintains the instrument optical geometry. Alignment is typically executed after the initial instrument deployment and after a major Flight System configuration change. The pointing control system includes coarse pointing and fine pointing described earlier. Coarse pointing acquisition and control actuates the siderostat motion to position and hold a target star image on the siderostat camera focal plane. Fine pointing acquisition utilizes the fast steering mirror control to position and hold the target star image location on the beam combiner focal plane. In addition, *angle feed forward* control algorithms are used to point the instrument on a dim science star using information from nearby bright reference stars. The pathlength control system involves control of the delay line in order to form a stellar fringe pattern on the beam combiner. Information from the internal and external metrology and the beam combiner are used to control the delay line in order to acquire a fringe and to keep the pathlengths through each of the interferometer arms equal. In the case of dim science targets, a *pathlength feedforward* control algorithm utilizes information from the guide interferometers and the attitude control system to estimate the correct position for the science delay line.

The onboard instrument electronics provide the real time processors, data busses, and component interface electronics necessary to control the SIM instrument. A total estimated processing throughput of several hundred MIPS is required on board to support command and telemetry streams concurrently with closure of the high rate pointing, metrology, and optical pathlength difference control loops in science operational modes.

A multi-processor architecture supports partitioning of software functionality across processors and microcontrollers for flexibility in subsystem partitioning, software development, and flight system implementation, integration, and test. Data bus latency requirements are driven by the closure of three concurrent sets of phasing control loops with sampling rates in the kilohertz range and the associated estimators, pointing control, and related functions. Redundant connection to the Mil-Std-1553B spacecraft bus is provided. Single fault tolerance capability also drives the maximum allowable latencies across the instrument data bus. Fault containment regions provide a robust design in the event of unanticipated electronics problems.

*Structures and Mechanisms*

There are two primary structures for the Flight System, each with a different level of requirements placed on it These are the "wing" or PSS and the "backpacks", the less precise part of the structure.

The Precision Support Structure design employs two deployable 'wings' sections to achieve the baseline lengths required for the science goals. Additionally, the PSS includes the nine meter metrology boom and "Kite" assemblies. These will also require deployment. The metrology boom mission stability requirements, as defined by the starting position of the "Kite" vertex position relative to the baseline, is 10 microns.

The "wing" has the seven siderostat bays integrated into it along with all the relay optics, optical switchyard, delay lines and beam combiners. The PSS has stringent, micron-level stability and thermal requirements placed on it.

The "backpack" attaches to the base of the PSS in two sections.. The first section houses the Spacecraft avionics and is referred to as the "spacecraft". The second "backpack" houses all the real-time control electronics that are not required to be in close proximity to their sensors or actuators. These backpacks include an isolation system to reduce dynamic disturbances and their impacts on the interferometer.

*Avionics*

The spacecraft provides the Flight System essential operational functions including power, attitude control, propulsion, communication and thermal control. The primary avionics suite is based on existing components developed at TRW. Most of the avionics components will be housed in the spacecraft backpack. The Command and Data Handling subsystem processor controls the spacecraft operation, PSS deployment, thermal control and interfaces with the instrument processors via the Mil-Std-1553 interface. The telecom system utilizes X-band communications. The Electrical Power Subsystem provides uninterrupted electrical power to the spacecraft and instrument, and employs a battery-clamped distribution bus providing DC power to all user loads via a solar array wing and a nickel-cadmium battery.

The attitude control subsystem (ACS) is an existing system providing 15 arc-seconds pointing accuracy per axis. The reaction wheel command and control laws are derived from the Advanced X-Ray Astronomical Facility (AXAF) vibration isolated wheels to provide pointing to 14 arc-seconds per axis and slew rates of 0.25 degree per second. Reaction wheel isolation will employ flight qualified isolators. To avoid disruption of science data solar array repointing and momentum unloading is performed during slew maneuvers. The propulsion subsystem is a proven off-the-shelf design used on previous NASA missions.

The thermal control subsystem is designed to meet the requirements on temperature stability and temperature gradients within the PSS and metrology boom. In the PSS, thermal stability is maintained at 20.0 +/- 0.1° C. Silvered-Teflon Multi Layer Insulation ensures that sunlight illumination will not adversely impact temperature stability. Thermal control of the spacecraft incorporates conventional aluminum heatpipes so that electronics and absorbed solar heating can be transported from the sunlit side of the spacecraft to the shadowed side.

## 3. TECHNOLOGY PROGRAM

The success of the SIM program relies almost entirely on the completion and proof of concept of new technologies being undertaken by a separately funded technology testbed program. A sequence of testbeds is under development to demonstrate and validate the fundamental operations and achievable performance of SIM. The results of these testbeds will be reflected in the design of the Flight Article. These testbeds and their primary objectives are summarized below.

*Microarcsecond Metrology Testbed (MAM)*

The Micro-arcsecond Metrology (MAM) testbed is a testbed that will demonstrate micro-arcsecond astrometric measurements of an artificial star that can not otherwise be done in ambient air. MAM includes much of the functionality of the flight system in a reduced scale experiment. The MAM testbed will include the interferometer, the metrology gauging system and the artificial star, all located in a vibration isolated, thermally stable vacuum tank. MAM is designed to achieve the same precision in white-light fringe detection and metrology gauge performance as SIM.

The MAM testbed will demonstrate that picometer metrology components can be configured in an interferometer to verify the position of a point source to the microarcsecond level. This experiment will be done at one-fifth scale in a 3 x 1 3-meter vacuum chamber. A 1.8-meter baseline interferometer will be used to observe an artificial star. The positions of the star and the interferometer are monitored by an external metrology system during the experiment, similar to the SIM flight design.

*Microarcsecond Metrology Testbed Plus (MAM+)*

A derivation of the MAM testbed, the MAM+ testbed is planned as a one baseline scaled-down version of SIM using a one baseline, articulating pseudostar. This testbed will demonstrate the measurements of an inverse interferometer pseudostar articulating over a 15 degree field of regard. This testbed will show performance accuracies comparable with the flight article and have test techniques that are traceable to the Flight System. The testbed also includes the validation of models to predict picometer performance.

*Microarcsecond Metrology Testbed Plus Plus (MAM++)*

The MAM++ testbed is an extension of the MAM++ testbed described above. It is three baseline scaled down version of SIM with a three baseline, articulating inverse interferometer pseudostar designed to measure flight level performance.

*Thermo-Opto-Mechanical Testbed (TOM)*

The TOM testbed will demonstrate temperature and surface figure control capability for a representative set of Collector Optics, predicted with a validated thermal-optomechanical model. The results of this testbed are required to be traceable to a SIM flight hardware design before the Project Implementation Phase start. The objectives of the TOM Testbed are: 1) to validate the integrated modeling capability, 2) to demonstrate capability to meet specific elements of the SIM Instrument thermal-deformation error budget i.e., to validate basic design approach, and to 3) to obtain measurements of thermal behavior and optical performance in an environment that simulates: a) the thermally stable test optic with and without cold aperture view factor and b) test the equivalency of the flight conditions: slewing the Siderostat Mirror over a 7.5-degree tilt (15-degree field of regard).

*System Testbed-1 (STB-1)*

STB-1 shown in Figure 3, was designed as a single arm interferometer and has been a testbed used to define and characterize disturbance sources, including representative reaction wheels. The main objectives of this testbed were to demonstrate that a positional stability requirement of less than 10 nanometers can be achieved in ambient air disturbance environment and predict that this requirement is achievable on-orbit. Demonstrating these requirements on this testbed is difficult as the testbed, like the Flight instrument itself, consists of many optical and mechanical components distributed across a 10 meter long flexible structure. As a part of the laboratory testing, this testbed is excited by mechanical disturbances, namely attitude control system reaction wheels, in order to characterize their effects on interferometer stability and control systems design. Results to date have shown that STB-1 has proven that less than 8 nanometer (nm) stability is possible in ambient air (see Figure 4), meeting and exceeding its performance requirements. Further, this testbed has been used to validate many of the integrated modeling tools that will be used in the design performance predictions of the flight SIM.

*System Testbed-3 (STB-3)*

The STB-3 testbed will be a fully functional 3-baseline interferometer operated in air. STB-3 will be the pathfinder testbed for many of the design trades and integration activities that would normally be associated with the flight instrument development. Developed in phases, the STB-3 will provide an opportunity to integrate incremental deliveries of control systems software, simulated spacecraft engineering functions and high precision laser gauging technologies. Key functional and performance requirements of STB-3 are to prove that nanometer-level pathlength stabilization is possible in ambient air. Specifically, STB-3 will establish the technology readiness to implement SIM Flight hardware vibration attenuation systems that provide: one nanometer Optical Path Difference (OPD) stability over one second integration time of a single baseline and ten nanometer OPD stability over one millisecond integration time of all three baselines[3]. This testbed will be built up in multiple stages. In the final stage, the testbed will reside on a flexible structure to more accurately predict flight performance and dynamics interactions. STB-3 will also establish the technology readiness to implement in flight software an autonomous real-time interferometer control system capable of operating SIM within the operational and control system constraints of the electronics systems. Other objectives of this testbed are to develop and document the integration and performance validation approach for the SIM instrument. STB-3 will also demonstrate closed and open loop control and data analysis and reduction software in all modes of instrument operation. Additionally, an end-to-end checkout of the entire system, remote alignment of the optical elements, exercise of full complexity of SIM and verification of the system are planned. The validation of system level requirements for accuracy, visibility and throughput are a key driver for this testbed.

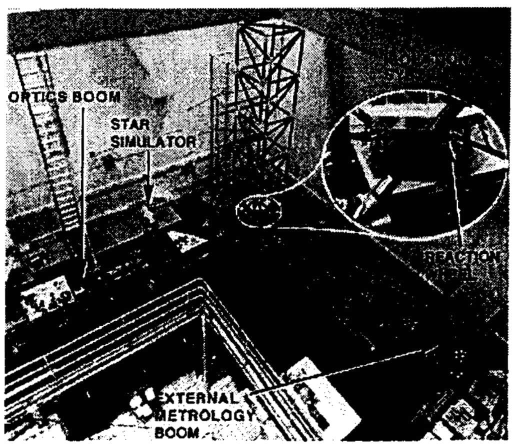


Figure 3 A View of the STB-1 Testbed

Additional goals for the testbed are to train the people, establish the procedures for integration and find out problems early in the SIM development cycle. Experiences gained by building a fully functional ground version of the instrument to the highest common fidelity possible will benefit SIM greatly.

By following flight like approaches to systems engineering, integration and test, the experiences can be captured in both documentation and knowledge in such a way as to be directly applicable to SIM, retiring risk earlier in the design process.

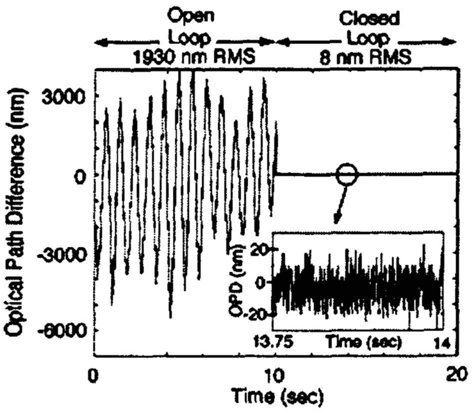


Figure 4 STB-1 8nm Closed Loop Results

*RICST*

The Real-Time Interferometer Control System Testbed (RICST) is an embedded real-time software testbed. A closed loop test environment is developed in the RICST facility that includes breadboard hardware components along with the software components. This testbed provides the facility and the environment for the testing of incremental deliveries and versions of software for an integrated interferometry program. The software under development will support multiple programs including both ground and flight interferometers. By using a core set of software code modules, incremental approaches to delivering SIM Flight Software should benefit the Project.

## 4. SYSTEM ENGINEERING PROCESS

A number of technical breakthroughs are required to enable the SIM mission, challenging the System Engineering task. As described above, a number of testbeds are being built to address key technology challenges. The function of the System Engineering and architecture task is to establish the requirements and design on the mission and instrument, translating into an engineering design the requirements and goals set forth by the Science Working Group. A summary of the driving requirements of the instrument are listed in Table 1. System engineering also has the responsibility to provide a link between the Flight Mission and a concurrent, separately funded interferometer technology development program described above, integrating the results of the technology testbeds into the Flight System design. The results of this technology development program, in the form of testbeds and models, will be applied to the analysis at the system level in order to determine whether the existing technologies and detailed designs have met the requirements of the SIM project. Over the course of the instrument development cycle, System Engineering will monitor the results of the technology development effort and correlate them into a validation and verification matrix. This matrix will be used in the integration and testing phase to prove that the system as a whole, meets or exceeds its mission objectives [4].

As is the case in the development cycle of any Flight Project, key reviews play a major role in examining the preparedness of the Project to proceed on to the next phase and as a forcing function to achieving pre-set Project schedule milestones. The

Table 1 Requirements Summary

| | |
|---|---|
| *Instrument Requirements* | |
| Max. Baseline Length | 10 meters |
| # of Baselines | 4 (2 guide, 1- 2 science) |
| Spectral Range | .4 - .9 microns |
| # of Siderostats | 7 |
| Aperture | 33 cm |
| Astrometric FOR | 15 degrees |
| Instantaneous FOV | 10 arcseconds |
| Sun Avoidance Angle | 45 degrees |
| Est. Mass | 3215 kg. |
| Fringe Stability | 10 nm (rms) |
| Pointing Control | 15 arcseconds |
| Pointing Knowledge | 5 arcseconds |
| Orbital Velocity Determination | 20 mm/sec |
| Spacecraft Slew Rate | 15 degrees in 2 min. |
| Temperature Stability for Critical Optics | 10 MilliKelvin / hour |
| Deployment Accuracy | 1 mm |
| *Science Performance* | |
| Wide Angle Astrometric Single Accuracy | <10 microseconds on 18th magnitude star |
| Proper Motion Accuracy | 3 arcseconds/yr |
| Image Dynamic Range | 20:1 |
| # of (U,V) Points per Baseline | 150 |

System Engineering Team is leading the preparation for these reviews. The SIM Project has significant Project-level reviews coming up in the next two years. These reviews are the System Requirements Review (SRR) scheduled for October 2000. The second review is a combined Preliminary Design Review (PDR) and a Non-Advocate Review (NAR) scheduled for the Fall 2001. The SRR is the review that establishes the formalization of the Project-level system requirements and conceptual design. The PDR/NAR is the review that is focused on a more advanced level of design and is the key "gate" which the Project needs to achieve in order to move beyond the Formulation Phase and into the Implementation Phases, formally known as Phases C & D of the mission.

The SIM Flight System Engineering Team has established a requirements development and allocation process to develop a comprehensive set of System and subsystem requirements. Utilizing a software tool called DOORS™ from QSS, Inc. the Flight System intends to capture all the requirements flowdown from the interferometer system level to the appropriate subsystem level, and provide a trace matrix for eventual validation of these requirements. The SIM team will make use of this tracing tool and a real-time team practice of levying and documenting it's requirements in a team-oriented, working environment. It is hoped that by use of an electronic method of maintaining and linking requirements at all levels, the old style of voluminous paper documentation can be eliminated. Further it is envisioned that unnecessary, redundant or un-allocated requirements will be found and eliminated. Additionally, a Project electronic library provides the repository for the interface and archiving of all major products, including these "documents". This library allows all elements of the Project to interconnect and have access to data that would otherwise be hard to find.

*Documentation*

Project documents are structured in a traditional maner, with requirements, design and interfaces being the primary focus (see Figure 5). Documents are provided at multiple levels per the Project Work Breakdown structure (i.e. Project System, System, subsystem, etc.) This team approach to requirements development will happen in an interactive forum. All system and subsystems requirements are negotiated and captured in electronic documentation. Each requirement is reviewed and allocated in real-time. In this fashion, each requirements is accepted, rejected, or modified. The requirements are then captured, in the appropriate documents and linked between the various levels of documentation through DOORS™. In this fashion, the full extent and impact of a particular requirement can be easily viewed and analyzed in context.

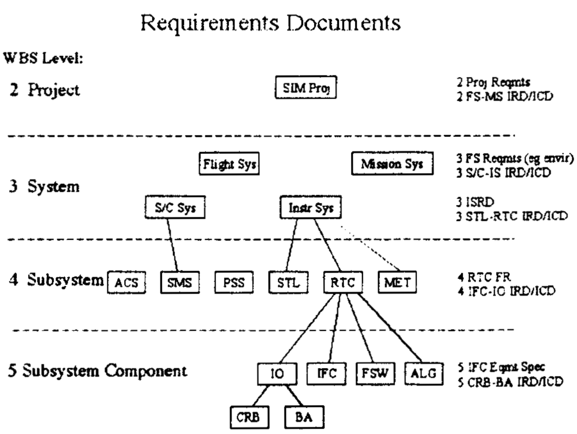


Figure 5 Representative Document Tree

As an additional tool for developing the system, error budgets have been generated that allocate detailed requirements to varying components of the system and predict system-level performances. These error budgets are a form of requirements and are processed, controlled and linked as such. There are two primary types of error budgets being developed; a nanometer error budget and a picometer error budget. The nanometer error budget applies to real-time on-board instrument performance while the picometer error budget implies detailed ground processing of the data to achieve picometer levels of performance. System-level trades are performed using the error budget as a method of contrasting and varying component contributions to the overall predicted performance. Specific items from the error budget are then tracked against results from the technology testbed program.

The System Engineering and architecture task has a complicated task coordinating not only classical subsystems-systems tiers, but has the added responsibility of forming and coordinating cross-cutting working groups as extension of its activity. These working groups have the responsibility to specify the detailed interface requirements and design issues across the breadth of the Flight system. The shear complexity of the interferometer creates complicated interfaces that have to be negotiated, documented and tracked. These working groups are divided along functional lines to address unique aspects of the system development and work out interface issues. The working groups include: Dynamics and Control, Thermal, Operations and Flight Software, Calibration, Integration & Test and Integrated Modeling. As currently envisioned these groups will address the following areas:

*Dynamics and Control Working Group*

The Dynamics and Control Working Group will develop an integrated design, which enables the Flight System to meet functional and performance requirements in the nanometer regime, that can be implemented for a low cost. This working group will analyze the impacts of flight system–induced disturbance sources on the optical performance and stability of the system. This group also defines the requirements and interfaces for the Flight System and subsystems.

*Thermal Working Group*

The Thermal Working Group defines the thermal control requirements, designs and interfaces. It is also responsible for the development, analysis and models of the thermal control schemes. The system is divided into two primary thermal control regions; those that require thermal stabilities in the +/- 1 degree Kelvin range, such as the precision structure, and the other region where extremely tight optical and metrology performance necessitates thermal stabilities of +/- a few milli-kelvin. For the various system orientations, it is this milli-kelvin thermal control that poses the greatest challenge to the thermal designers. Specifying the interfaces and cross-coupling between these zones is an important part of the Thermal Working Group effort.

*Operations and Flight Software Working Group*

The Operations and Flight Software Working Group is defining the Flight System Operations concept, including application of the mission timeline, operations scenarios and flight system modes and states. Further, this group is addressing key issues related to the development of the system and subsystem derived software requirements architecture. Key software interfaces, requirements, partitioning and constraints are being defined in preparation for the SRR and PDR milestones. Development of a Flight information system high-level architecture, along with defining the design details of data transfer, packaging and management are necessary goals for a coordinated system design. Further, this working group provides a conduit for information and system-level trades between the Ground System and the Flight System and documents those partitions in a series of interface requirements and design specifications.

Calibration Working Group

The Calibration Working Group is chartered with defining the ground testing and on-orbit Flight System calibrations necessary to derive the primary science data. This working group plays a supporting role to the Integration and Test activity. Its primary objective is to capture the Calibration approaches and requirements and produce a Calibration Plan. Aspects of coordinate frame, optical, mechanical and electrical calibrations are being derived by this group. Further, the group is analyzing the pointing of critical optics. Effects that impact optical delay or distance measurements and the interactions with the sensor suites are also being studied.

*Integration and Test Working Group*

The Integration and Test Working Group is developing an overall Project test-flow schedule for the assembly and test of both the Interferometer and the Flight System. This activity, as with all Space missions, is a complicated and critical schedule driver for the mission. The two Industry partners, Lockheed Martin and TRW, are both delivering the major components of the Flight System. As such, each has its own separate integration and test activities that require verification and validation that the system meets its requirements. These two "halves", the Interferometer and the Spacecraft, must come together in Assembly, Test and Launch Operations (ATLO) activities prior to the final mating with the launch vehicle. A detailed workflow and schedule of this activity has been generated. This working group will produce the requisite requirements for the testing program and provide an Integration and Test Plan.

*Flight System Integrated Modeling*

The Flight Integrated Modeling effort is divided up into two portions; a Flight nanometer modeling activity and Flight picometer modeling activity. The nanometer modeling activity has, as its primary objective, to build and exercise nanometer level models of the Flight System that will verify that the SIM system level performance/requirements can be met. A second objective is to support the System Engineering effort with detailed analysis for validating the error budget requirements. This activity both helps define and verify system-level performance requirements and provides predicts of on-orbit performance of the flight system. The picometer modeling effort is responsible for modeling the interferometeric response of both starlight and metrology at the picometer level. This includes modeling the affects of thermal, optical, structural, and electronic phenomena that affect the flight system's ability to measure picometers. Examples would be (1) models of the change in the instrument thermal environment at the milli-kelvin level and how this effects optical output, (2) predicting system level beam walk effects due to real mirror surfaces and various misalignments/positioning, scenarios, etc.

*Testbed Modeling*

To better understand the results of these models, the SIM Technology Testbeds are also being modeled, using the same techniques and approaches as the Flight System models.. These models will be compared and contrasted to the testbed data. Correlation between the testbed model predictions and the testbed results will better verify and build confidence in the use of these models for the Flight System predictions (see Figure 6). As each testbed demonstrates one or more critical SIM functions or capabilities, the process of developing these models will also serve to illuminate the counterpart model development tasks concurrently underway for SIM. These models will be contrasted with actual results extracted from the testbeds. The models will be updated and modified, as necessary, based on the testbed results. This approach is required to be verified by NAR, as a precursor to the Project proceeding into the Implementation Phase.

*SIM Simulation modeling (SIMsim)*

The operation of the instrument is extremely intricate, involving the interaction of many subsystems that control the optical elements, the dynamic and thermal environment system, and spacecraft operations. The modeling of these interactions at both a functional or cross-cutting level and at the detailed subsystem level, necessarily encompasses several disparate disciplines and requires an integration of the models to yield a system level understanding and characterization. Additionally, a complicated system-level modeling process, defined to examine whether the Flight System requirements meet the science objectives are met has been undertaken. This process, SIM simulation modeling, or SIM-sim, uses reduced versions of the complicated models mentioned above in addition to a data model of the Flight System (see Figure 7). The output of SIM-sim will answer whether flight system design is adequate to meet science requirements.

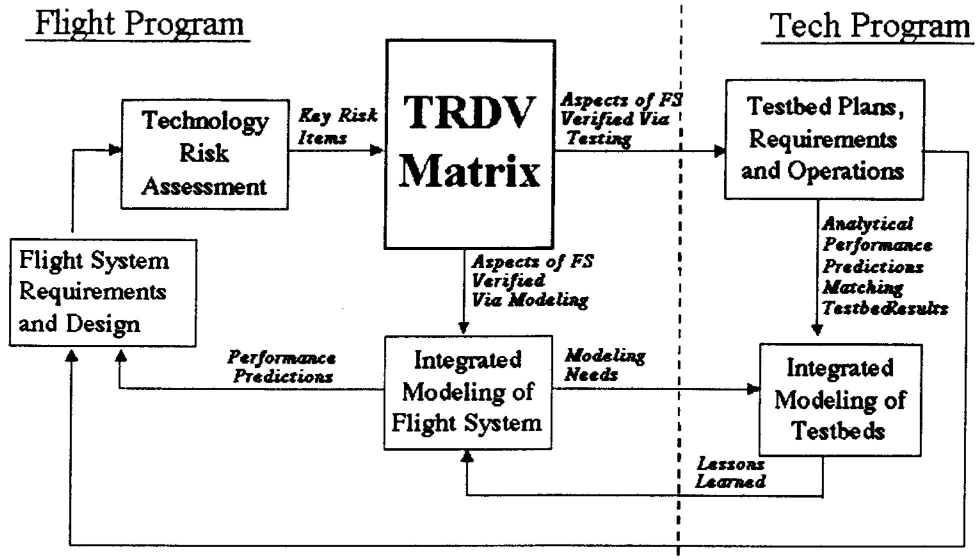


Figure 6 SIM Requirements Development and Modeling

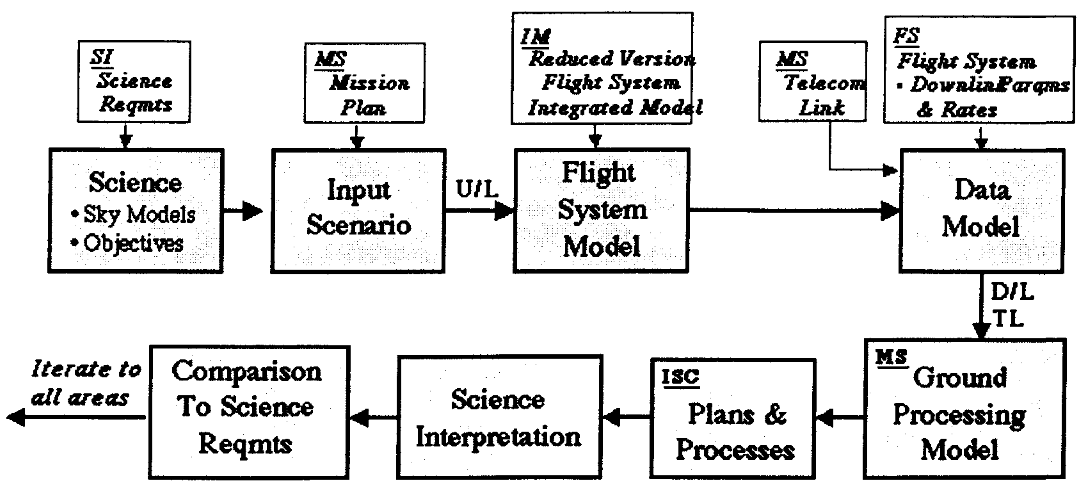


Figure 7 SIM Simulation Modeling (SIM-sim)

The System Engineering activity has developed a process, referred to as the "Tapestry", to describe the whole requirements validation, verification and risk reduction process to be undertaken. This process assumes that when the Flight System requirements and design are complete, the SIM project has to demonstrate, by NAR, that: 1) The Flight System requirements and design are adequate to meet the Science requirements, 2) the key required technologies are demonstrated, 3) the System design, calibration, and operation has been functionally modeled 4) the modeling and test program is adequate to predict in-flight performance, 5) the implementation of the design is reliable and 6) a reasonable plan for fault analysis and risk mitigation is in place.

These "Tapestry" activities are a precursor to normal Flight System Verification activities. They are also a subset of the risk management activities and focus on Flight System areas that require early detailed attention and careful follow-up.

One piece of the "Tapestry" implementation is the Technology Requirements and Development Verification Matrix (TRDV). The TRDV (see Figure 8) is the engine of this process, tying together the Flight System requirements from the error budget allocations to the performance requirements on the individual technology testbeds. Using this linkage between the flight needs and the technology responses, it is hoped that a significant amount of program risk reduction will be achieved, prior to the Implementation Phase of the Project.

A Validation and Verification Matrix uses the analysis of technology testbeds to support the design of the Flight article. The Validation and Verification Matrix is a system engineering method that tracks how, where and by what process requirements are proven. Some requirements are validated at a component or subsystem level. Other requirements demand system level test. Other requirements, can only be validated by analyses. Over the course of the instrument development cycle, the System Engineering team will monitor the results of the technology development effort and correlate them into a validation and verification matrix. This matrix will be used in the integration and testing phase to prove that the system as a whole, meets or exceeds its mission objectives.

*Prioritized list of key risk items*

**TRDV Matrix**

| | Formulation Phase | | Implementation Phase | | |
|---|---|---|---|---|---|
| **Milestones** | **Testbeds** | **Modeling** | **I&T** | **Modeling** | **Anal.** |
| 1. Guide OPD jitter < 10nm | STB1 STB3 | Dynamics Model | X | X | X |
| 2. Starlight path measured to 100pm | MAM | ITOM | X(?) | X | X |
| . | . | . | . | . | . |
| . | . | . | . | . | . |
| . | . | . | . | . | . |

*Plans &Requirements for:*
1. *Testbeds*
2. *Integrated Modeling*
3. *Flight I&T*

Figure 8 Technology Readiness Development Matrix

## 5. CONCLUSION

This paper has described the detailed SIM reference design and a number of the technology testbeds that are addressing major risk areas early in the program. System Engineering will use the testbed results and models to validate that the SIM mission will meet it's on-orbit performance requirements in an effort to reduce or mitigate risk earlier in the design phase of the mission. Numerous System challenges have resulted in the implementation of system cross-cutting working groups to address various functional, performance and interface aspects of the Flight System. The System approach, as described, is to optimize the design process, produce testbed and model results in the Formulation Phase of the Project along with finding innovative ways of meeting the overall Project objectives and constraints while reducing risk.

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